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Title: Radiographic Detector Development for DARHT and ASD Scorpius (U)

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Radiographic Detector Development for DARHT and ASD Scorpius (U)

Jacob Mendez

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Radiography has been used to validate and understand implosions since the Manhattan Project

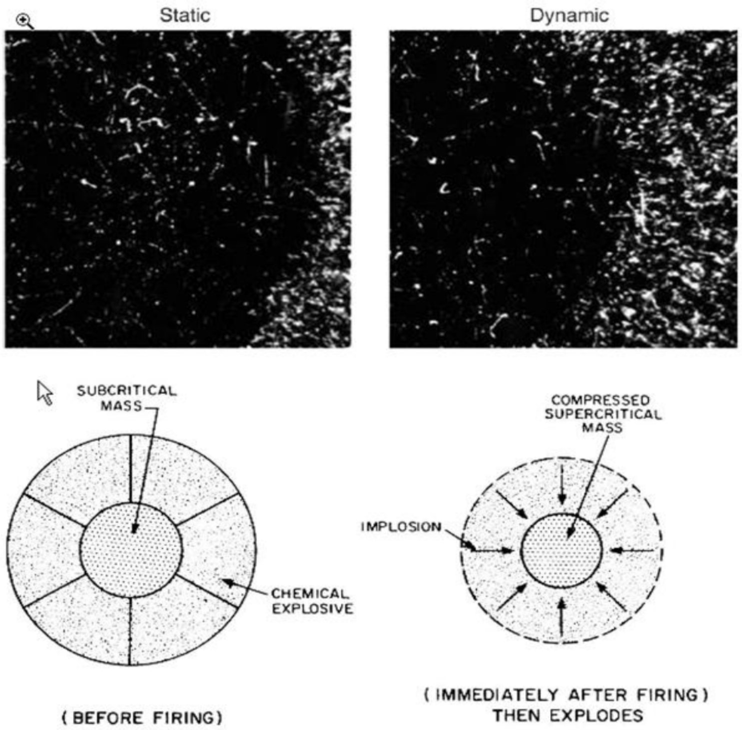

Figure 1. Manhattan Project radiographs of an explosively driven implosion experiment (1944). The x-rays were generated with a 15-MeV betatron and recorded on a Wilson cloud chamber[4].

Figure 3. The Radiolanthanum Experiments
This photo taken at Los Alamos during the Manhattan Project shows the “remote handling” of a kilocurie source of radiolanthanum located inside a lead container. This strong gamma-ray source would be placed at the center of a hydrotest assembly to measure the areal density of the pit (from the center outward) as a function of time.

Modern stockpile stewardship needs the capability to perform penetrating (DARHT-class) radiography on dynamic SNM objects

Dual Axis Radiographic Hydrodynamic Test (DARHT)
Multi-Pulse, Multi-Axis – Highly Penetrating Radiography
Limited Test Material Options

U1a Facility at Nevada National Security Site

Cygnus Radiography

Cygnus/U1a
Multi-Axis – Modestly Penetrating Radiography
SNM Material Options

DARHT-Class Multi-Pulse Radiography

U1a Facility Test Material Options

ASD Scorpius

LANL has been assigned lead of ASD but is relying on expertise across the complex.

Project Director	Dave Funk
Project Manager	John Tapia
NV On-Site Deputy	Colburn Kennedy (LLNL)

Technical Director	Mark Crawford
Chief Engineer	Juan Barraza
Chief Scientist	Carl Ekdahl

Project Office is based at LANL

Work Breakdown Structure Level 3 Leads

WBS	Area	Level 3 Lead
1.2.1	Injector	Josh Leckbee (SNL)
1.2.2	Accelerator	Greg Dale (LANL)
1.2.3	Downstream Transport	Jennifer Ellsworth (LLNL)
1.2.4	Detector	Jacob Mendez (LANL)
1.2.5	Global Systems	Juan Barraza (A) (LANL)
1.2.6	U1a Interface	Al Meidinger (NNSS)

Senior Team Leads

Lab	Senior Team Lead
LANL	Stefani Swickley
SNL	Jon Custer
LLNL	Brian Guidry
NNSS	Darryl Droemer

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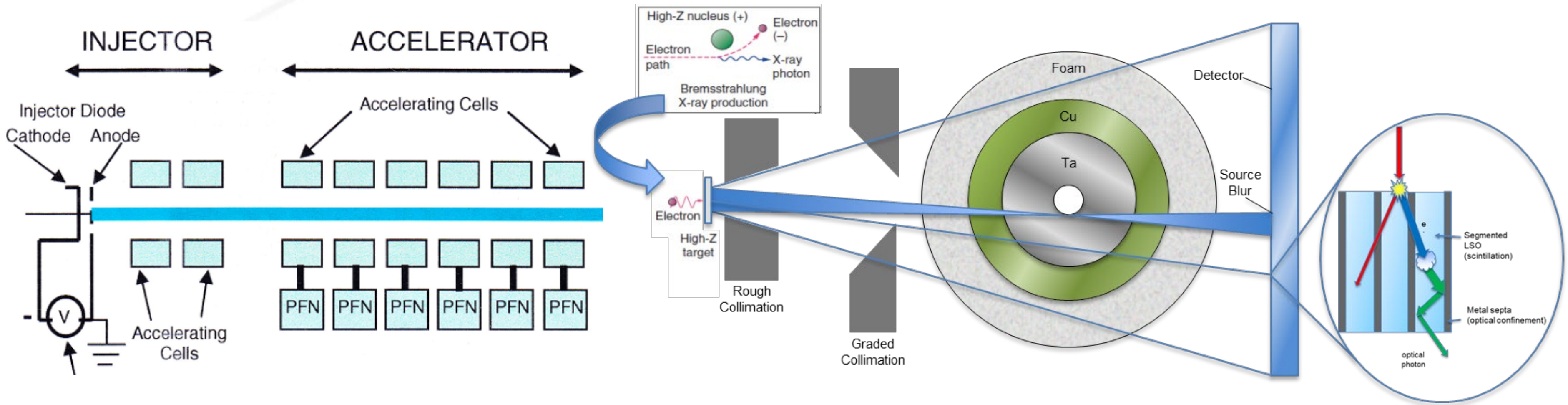
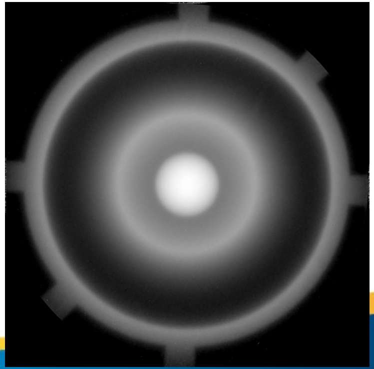
Modern Radiographic Chain



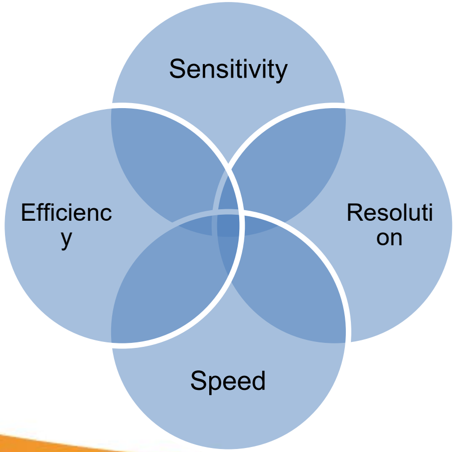
- Test objects are very dense requiring high source x-ray doses and sensitive detector systems
- Features in dynamic objects are moving very fast (>mm/μs) requiring short radiation pulses to freeze motion
- Features of interest are small (<1mm) requiring small source spots and high-resolution detector systems

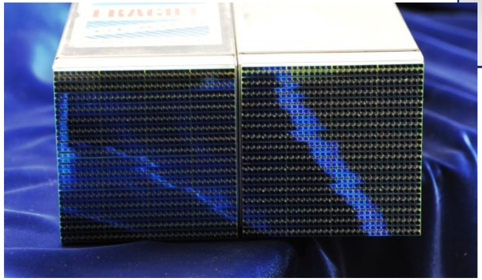


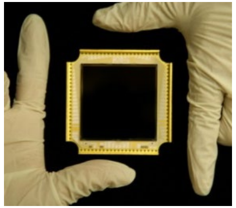
The Los Alamos Gamma Ray Camera (GRC)

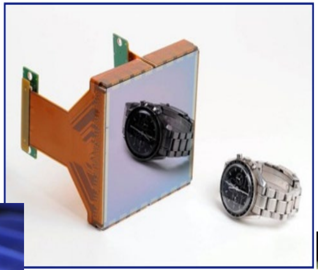
LANL GRC's are the largest, fastest, and most sensitive detectors in the world and are capable of capturing sub-millimeter resolution radiographic images

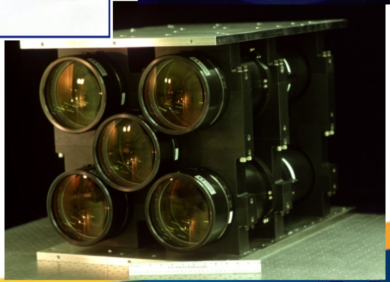
- Are a critical component of radiographic systems *(Past, Present and Future)*
- Offer unique capabilities for eXtreme imaging
- Offer world-class performance
- Combine resolution, speed, efficiency and sensitivity











Preliminary design uses, dose equivalent, detective quantum efficiency (DQE) as the primary design metric

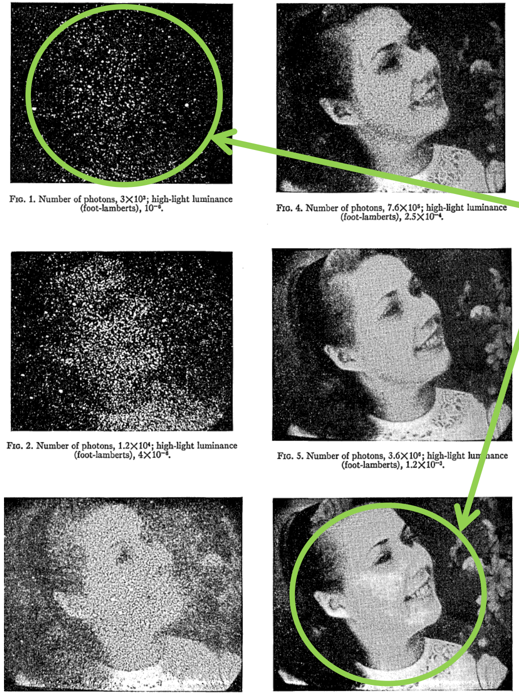


Fig. 1. Number of photons, 3×10^3; high-light luminance (foot-lamberts), 10^{-6}.

Fig. 2. Number of photons, 1.2×10^4; high-light luminance (foot-lamberts), 4×10^{-6}.

Fig. 3. Number of photons, 9.3×10^4; high-light luminance (foot-lamberts), 3×10^{-5}.

Fig. 4. Number of photons, 7.6×10^5; high-light luminance (foot-lamberts), 2.5×10^{-4}.

Fig. 5. Number of photons, 3.6×10^6; high-light luminance (foot-lamberts), 1.2×10^{-3}.

Fig. 6. Number of photons, 2.8×10^7; high-light luminance (foot-lamberts), 9.5×10^{-3}.

$$DQE(f) = \frac{SNR^2_{recorded}}{SNR^2_{incident}} = \frac{MTF(f)^2}{n\,NPS(f)} \propto \frac{1}{1+\frac{1}{n}}$$

- DQE of primary photons is dominated by the x-ray to visible light converter (Scintillator)
- Film/Phosphors ⇨ DQE~0.1%
- 4cm LSO ⇨ GRC DQE ~50%
- Scintillator Density (7.4g/cc*)
- Scintillator Light Output (30k phot./MeV*)

- DQE of secondary photons is dominated by the visible optics of the system
- Efficient Light Transport ⇨ $n = \dfrac{QE_{CCD}\,GM^2}{8\eta_i^2 F_\#^2 (1+M)^2}$

Equivalent to dose, the DQE of the detector is a very important design consideration for any radiographic capability….

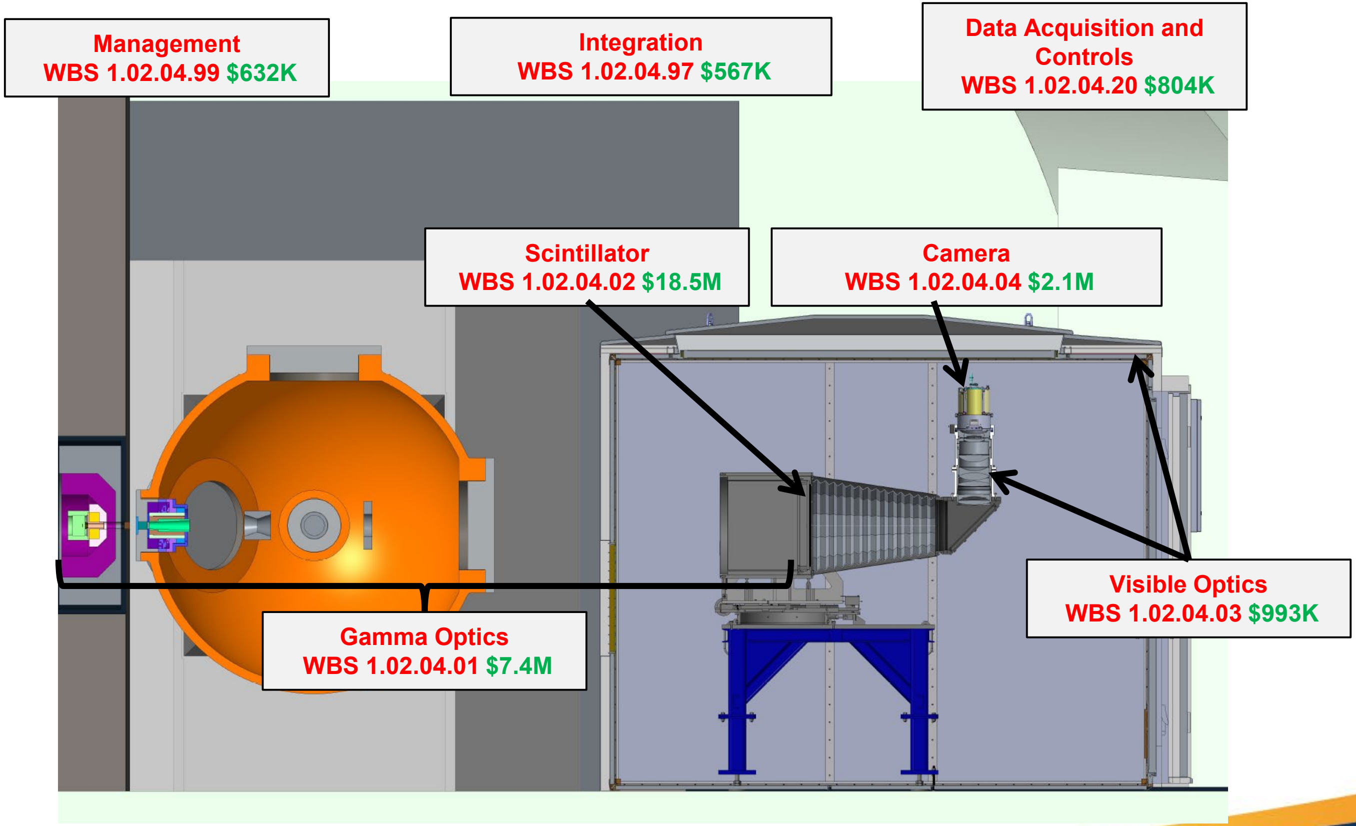
Key performance parameters highlight important detector design parameters

Key Performance Parameters for Radiography	Relevant Detector Design Parameter
Density Discrimination and Uncertainty	Detective Quantum Efficiency (DQE) x-ray Fluence Source/Detector Collimation/Shielding Neutron Production and Shielding Radiographic Magnification Source Collimation Scintillator Area Imager Area
Uncertainty in Location of Features	Modulation Transfer Function (MTF) Contrast to Noise Ratio (CNR) x-ray Fluence Radiographic Magnification Scintillator Thickness/Element Pitch Source/Detector Collimation/Shielding Neutron Production and Shielding
Field of View	Radiographic Magnification Source Collimation Scintillator Area Imager Area

The detector design scope is broad. Properly designed interfaces are required to maximize data quality

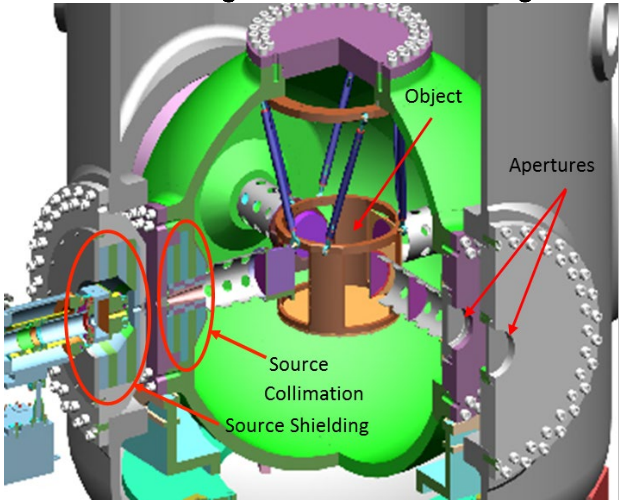
	Reference Detector Requirements	Ref. Req.
Variable Gate	Ability to adjust framing width and spacing independently for four images	2a,b,c
Overall Capability	System Resolution, Sensitivity, and Field of View equivalent to DARHT-1 (Spot size limited regime)	2a
Imaging Flexibility	Adjustable radiographic magnification and conjugates to support wide range of experiments	2a
Scatter Control Flexibility	Ability to perform radiography with or without a scatter control bucky grid	2a
Remote Operation	Ability to operate system without access to Zero Room	3a
Noise Sources	Minimize impact of non-radiographic radiation sources	5a
Relocation/Realignment	Capable of moving GRC > 5 m downstream and then realigning to ±2.5 mm	2a
Source to Detector Alignment	±250 μm offset (X,Y,Z), ± 0.01 degrees rotation (X,Y,Z)* *with Bucky Grid	2a
Fit in U1a	Allow downstream components to pass without significant delay and all hardware must allow for reasonable installation, maintenance, troubleshooting, and replacement.	1a,3a
Thermal Management	All heat sources will reject the majority of generated heat to the water exchange system	1a
Beamline height	1.5 m from reference floor	1a
Reliability	Component reliability to be demonstrated consistent with .995 radiographic reliability	3a

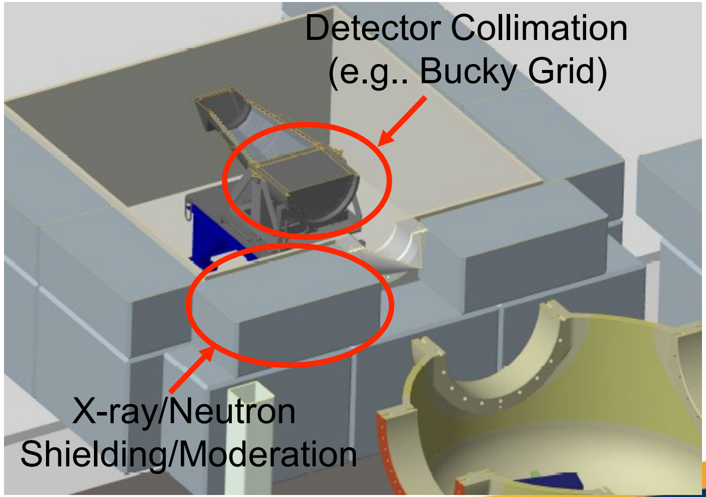
Detector WBS 1.02.04; $31.2 M



Gamma Optics: Design objective is to minimize scatter generation and detection

- Source Collimation and Shielding
  - FOV Definition ⇨ (Scatter reduction from object and apertures)
  - Target Box Shielding (x-rays, neutrons, electrons)
  - X-ray Aperture Material ⇨ Minimize production of (γ,n), (n,γ) etc., and areal mass
- Detector Collimation and Shielding
  - Scatter Reduction Techniques ⇨ Bucky Grid
  - Boron loaded poly/concrete, steel, Cadmium etc. (Material Optimization)
- Design based on modeling efforts validated by empirical data





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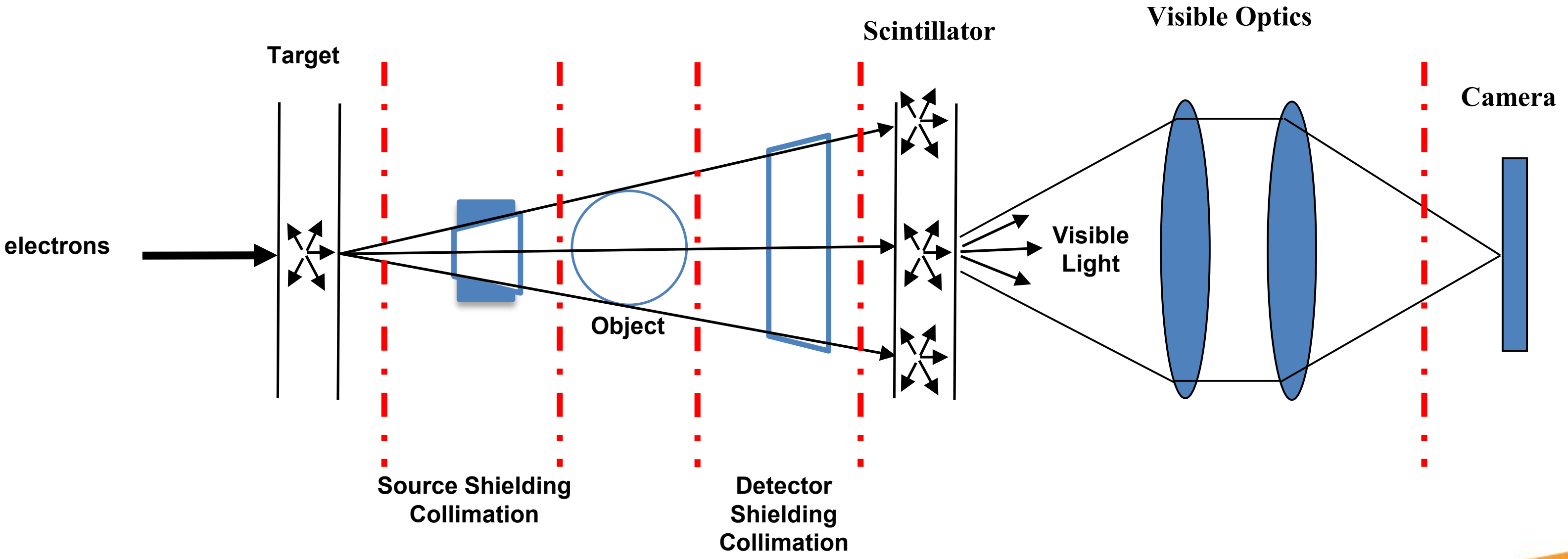
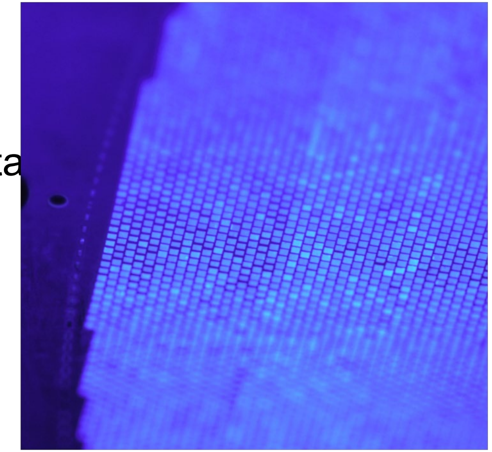
The Gamma Optics preliminary design will be based on DARHT geometries and optimized for Scorpius

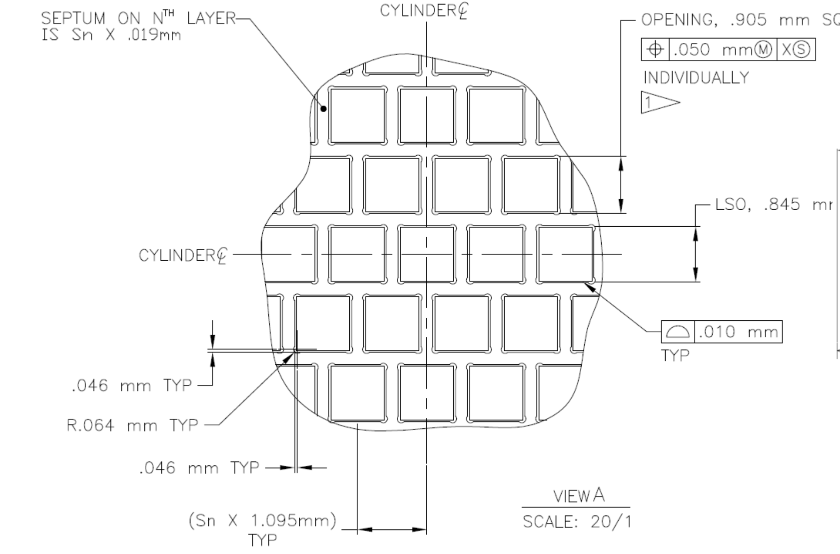
- Models of relevant DARHT geometries will be generated using MCNP codes.
- The model will be evaluated at various tally planes denoted by red dashed lines below.
- Empirical data will be acquired at DARHT in relevant locations and used to validate the model.
- The model will then be optimized for Scorpius radiography.

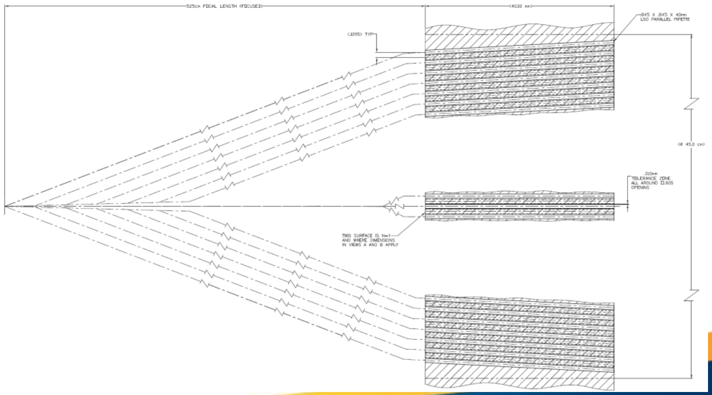


Preliminary design of the Scorpius scintillator was based on the DARHT segmented LSO scintillators

- Steel septal walls isolate visible light.
- Focusing reduces parallax due to diverging x-ray beam.
- TIR light is maximized with air gap between septa wall and crysta
- 40.0 mm thickness for good primary photon DQE
- 1mm pitch for good object sampling resolution

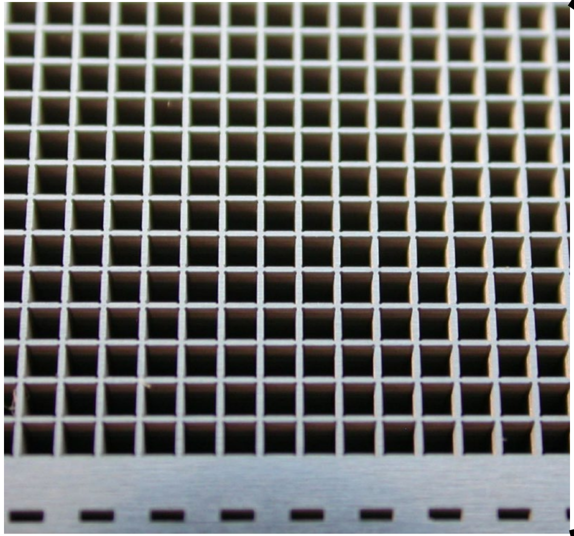


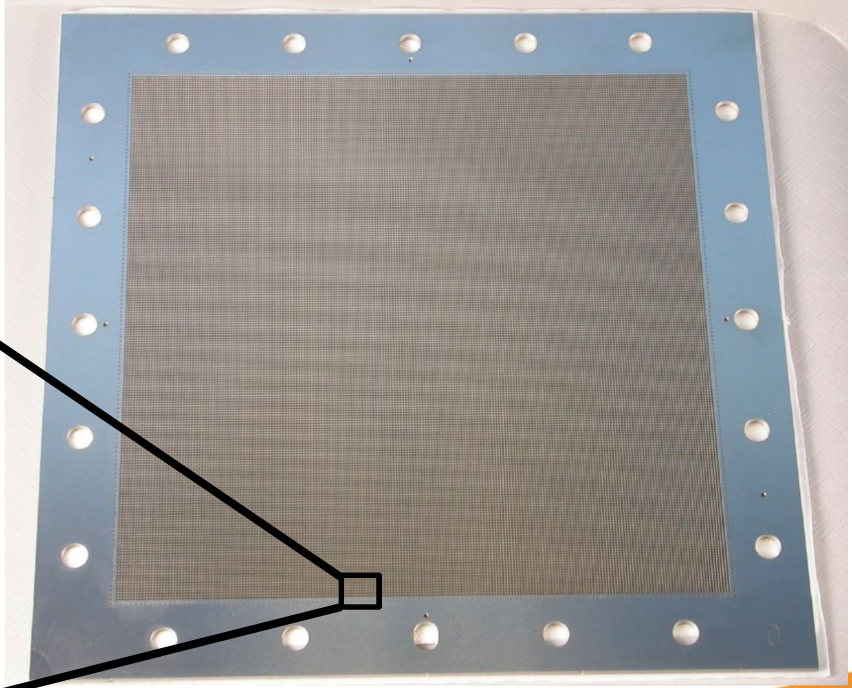




Scorpius Prototype Scintillator fabrication is progressing

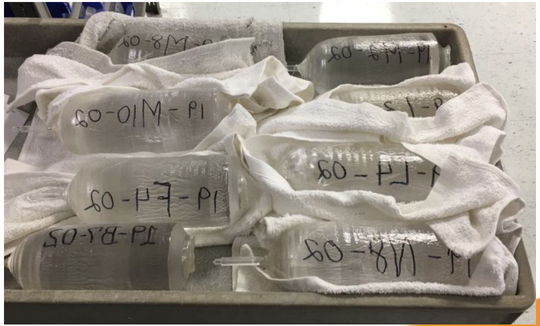
- A 1/10 thickness test stack was completed in January
  - Test stack grid contructed from 54 layers, each 0.003" thick
  - Average total height measured: 0.1626"
  - Calculated thickness per layer (0.1626/54) = 0.00301
  - Estimate that 526 layers needed for 40.25 mm thickness
  - 0.034" (0.865 mm) square test pin fit easily in all areas.





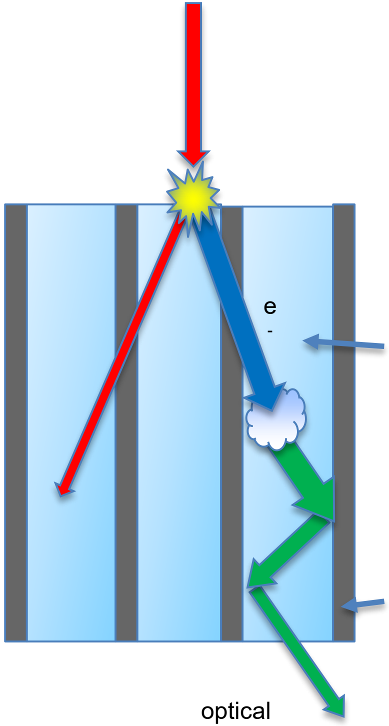
Vendor capability established for growth and fabrication of scintillator elements. (LSO or LYSO)

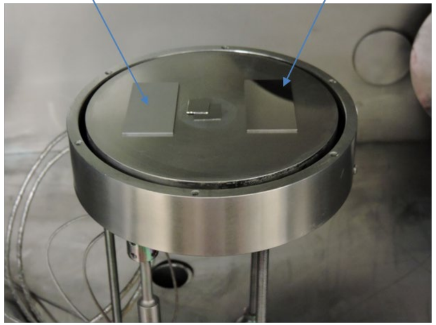
- Crystal Photonics Inc., is presently supplying fully processed LSO crystal elements for a spare DARHT scintillator.
  - 50,000 units delivered to date.
- Staff toured CPI's facility and found the operation to be quite impressive.
  - Plenty of bandwidth to meet DARHT and Scorpius needs
  - Largest supplier of LYSO in the world (Medical Imaging PET Scanners)
  - Willing to grow/fabricate smaller material lots.



Advancing toward quantitative evaluation of all scintillator components, best configuration for Scorpius

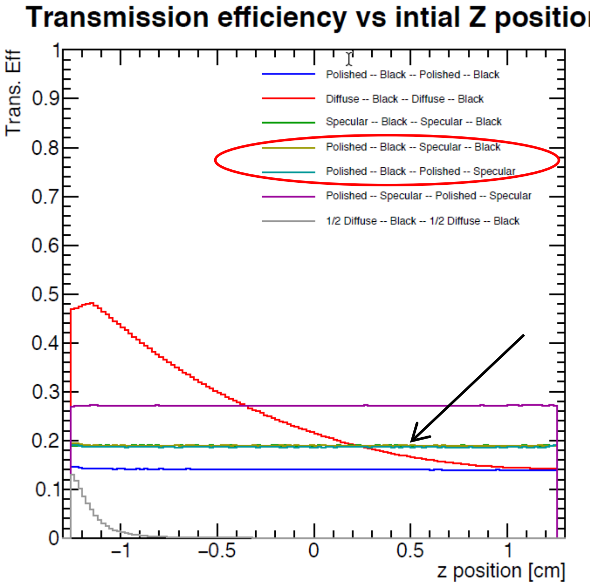
- Polymer back-reflector:
  - Analytical models and data show a back-reflector can improve optical transport efficiency
  - Develop thin-film direct coatings on LSO for evaluation
- Metal septa and optical transport:
  - MCNP models suggest improvements going to high Z septa
  - Collaboration with XCP-3 to develop further MCNP and GEANT models, detailed laboratory characterizations
- Gamma Ray Sensitivity Optimization:
  - Further work required to understand potential impact of other proposed changes

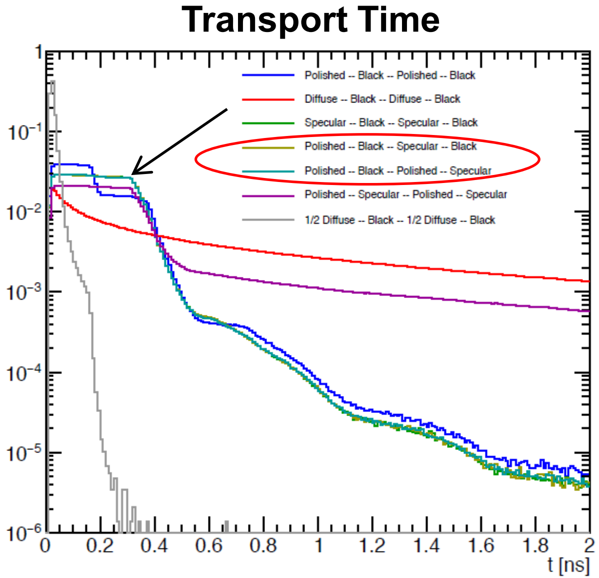




I. Usov and D. Vodnik, MST-7

Initial idealized optical modeling shows how surface treatments on scintillator elements would behave

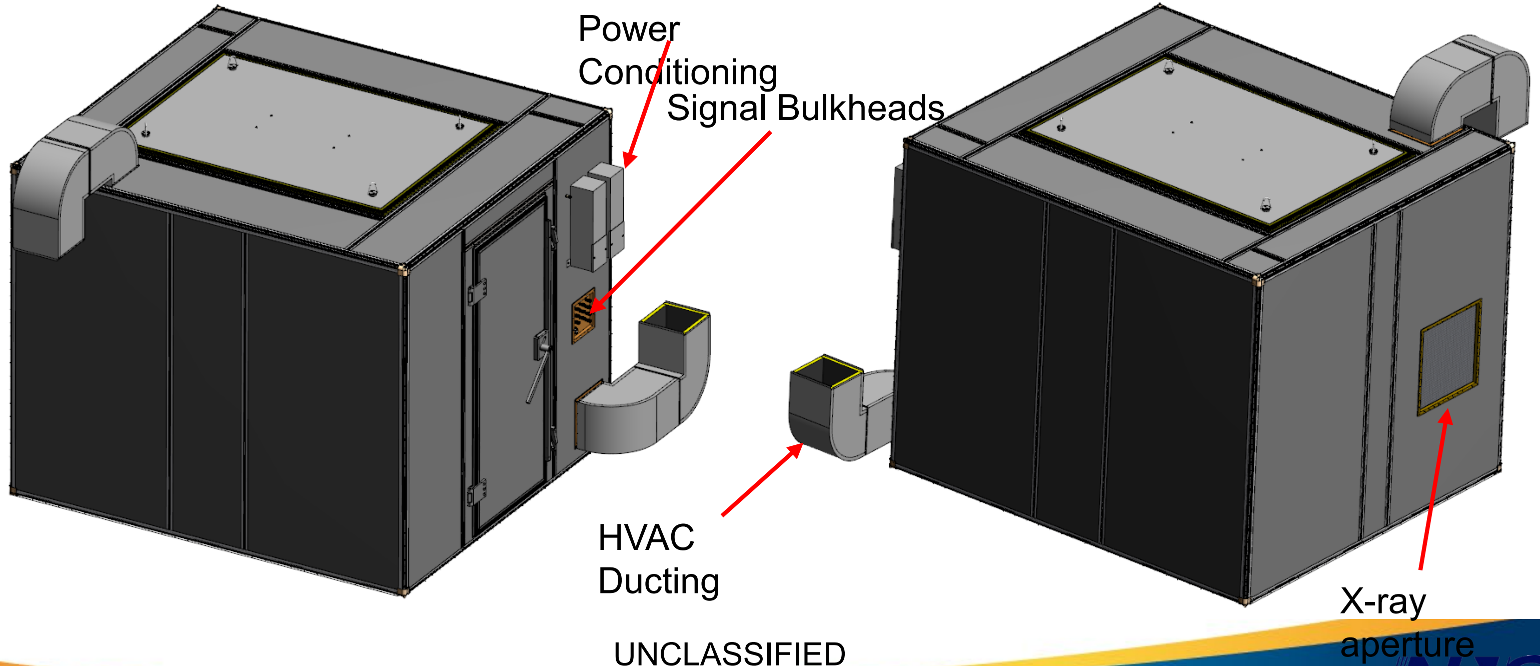




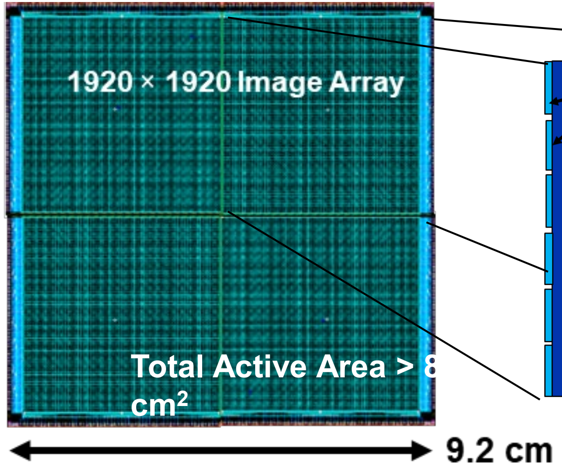
- Applying a reflective coating on the top face of the crystal (cyan) an increase in efficiency (~20%) without degrading time response.
- Experiments planned to obtain optical properties and characteristics from relevant materials using MeV sources.
- Data from the experiments will feed optical modeling inputs and make results more robust.

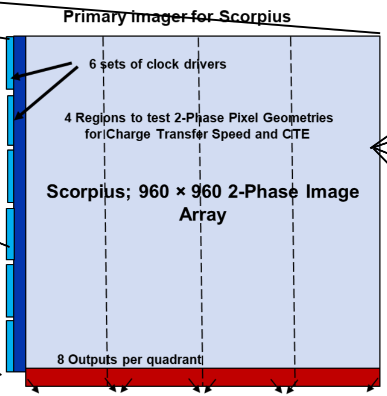
The light sensitive detector components must be shielded from ambient light

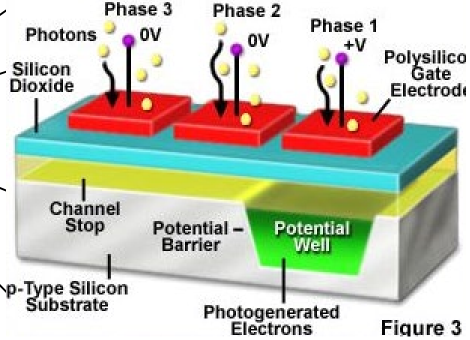
- A light tight enclosure that also provides isolation from noise sources (rf, thermal, scatter etc.) is essential.
- Provides local power conditioning, isolated electrical/optical bulkheads and low Z x-ray aperture.

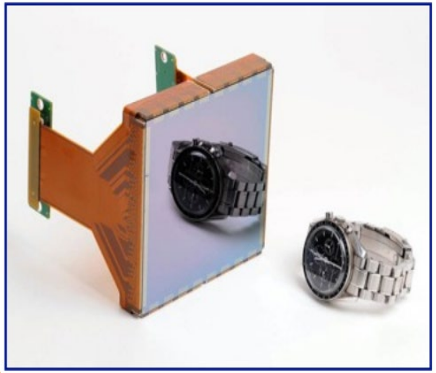


A simpler, two phase Scorpius imager can benefit yield. Also allows larger active area for improved efficiency to secondary quanta.









- Dedicated Scorpius imager design effort underway at MIT-LL
  - High-Efficiency, High-Speed imager for thick objects (4 frames @5 Million Frames per Second)
  - Simulations are investigating charge collection/transfer speed, and CTE over a wide range of design variables.
- Next Generation DARHT Axis II imager design effort may provide additional capability and risk mitigation for Scorpius
  - High Speed, High-Frame Depth imager for thin objects (8 frames @ 4 Million Frames per Second)

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Present camera design efforts meet some requirements but not all

Parameter	ASD (Threshold Requirement)	ASD (Objective Requirement)	DARHT 2 (Existing CCID-36)	DARHT 2 (CCID-91 Requirement)	Notes
Frame Rate (MHz)	2	5	2	4	
Number of Frames	2	4	4**	8 **	** Meets Objective
Inter-Frame Time (ns)	500	200	500*	250	*Meets Threshold
Pixel Size (μm)	≤48	≤48	96	48	
Active Area (cm^2)	>36	>36	25	36	
Dark Current (e^-)	<5	<5	100	<5	
Frame Isolation	≥1000:1	≥1000:1	500:1	>1000:1	
Dynamic Range (bits)	≥16,000:1	≥16,000:1	16,000:1	16,000:1	
Read Noise (e) rms	≤3	≤3	5	3	
CCD Quantum Efficiency	≥80%	≥80%	55%	80%	

Optimization present opportunity for dramatic improvements in detector performance vs. DARHT benchmarks

- Potential for significant improvement in signal
  - Demonstrated 2X improvement with new DARHT A1 lens
  - Removal of intensifier: ~1%
  - Improvement of back-reflection: As much as 2X
  - Addition of index-matching at optical output: ~15%

    —> ~4X improvement in secondary photon quantum efficiency

- Potential for significant improvement in signal to noise
  - Demonstrated 40% improvement in DQE with new DARHT A1 CCD
  - Potential for additional 30% improvement (at 0.4 lp/mm) with optimization of the septal frame structure

    —> 70% improvement in signal-to-noise

Backup Slides

Modern Radiographic Chain